Estimating the outer scale in altitude - $L_0(h)$ - using the GeMS profiler

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ABSTRACT

We analyze the altitude distribution of the turbulence outer scale - $L_0(h)$ - at Cerro Pachón from Gemini South MCAO (GeMS) loop data. GeMS turbulence profiler is fed with telemetry from their 5 WFSs and from the voltages applied to the deformable mirrors, providing estimations of r_0, C_n^2(h), wind profile (speed and direction for every layer), isoplanatic angle and the outer scale distribution $L_0(h)$. It is shown that this last parameter ranges from less than 1 meter at the ground to more than 50m (the telescope is insensitive to larger cannot detect differences above this value). The technique is based on cross correlations of the pseudo-open-loop slopes that allow to disentangle the multiple constituents of L_0.

Keywords: Atmospheric turbulence, outer scale, adaptive optics

1. INTRODUCTION

Existing work on L_0 estimation have shown that strong disagreements exist on the results, the way it is estimated and its importance in AO areas such as PSF-R, tomography and turbulence profiling and ultimately system design for ELT instruments.

One common approach to estimate the outer scale (L_0) is to assume it as a constant parameter and some work has been done towards developing models for its behaviour in altitude, $L_0(h)$ [1,2]. However, the results show that no general consensus exist on the characteristics of this parameter.

In this article, we intend to contribute to the knowledge about this parameter by analysing a significant amount of data collected at GeMS during three years of campaigns and also developing a technique to estimate the outer scale profile.

2. GeMS AND ITS TURBULENCE PROFILER

GeMS is the Gemini South multi-conjugate AO system. It uses 5 laser guide stars with their associated WFS and 3 DMs (currently only 3) to compensate the turbulence over a field of view of more than 1 arcmin. Three natural guide stars control of the tip-tilt and plate scale modes.

The GeMS profiler [3] is based on getting the cross-correlation maps from the pseudo-open-loop slopes for single frame data. Wind profiles (moving layers), are detected by cross-correlating relatively delayed frames.

For T = 0 s, the turbulence profile in altitude is extracted from the baseline between two WFS. For T > 0, the layers present can be detected and their velocity estimated (see Figure 2).

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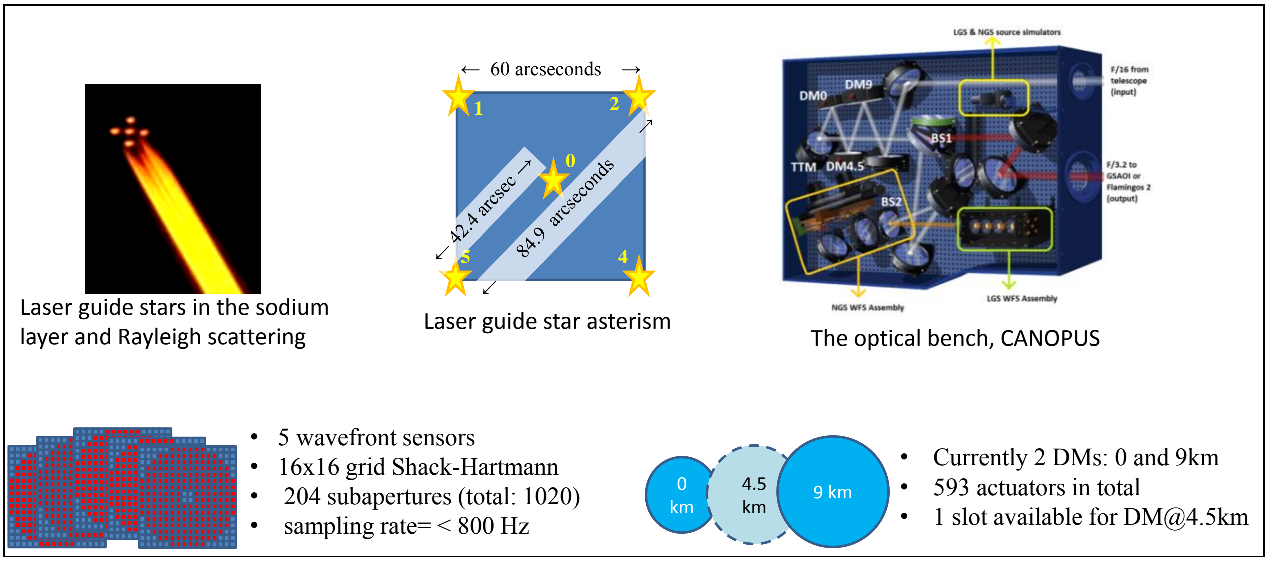

Figure 1. GeMS: It comprises 5 laser guide stars with their associated WFS and 3 DMs (currently only 3) to compensate the turbulence over a field of view of more than 1 arcmin. Three natural guide stars are used to control of the tip-tilt and plate scale modes

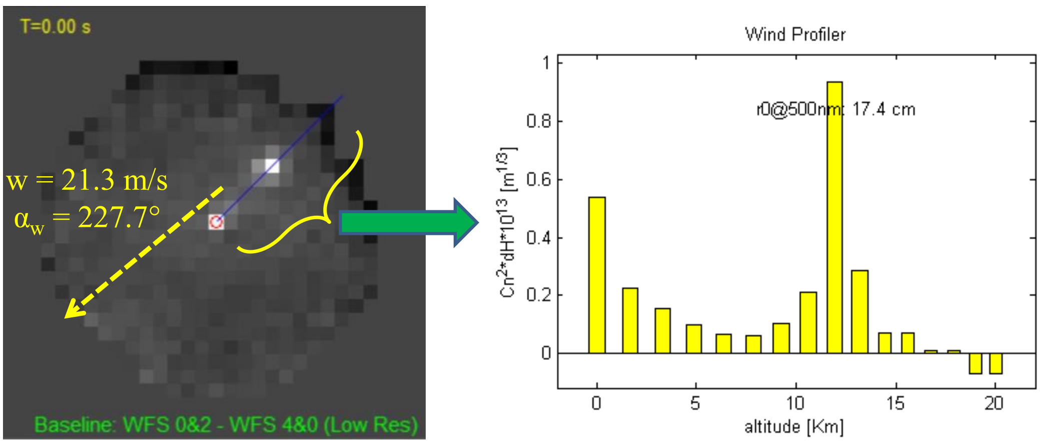

Figure 2. GeMS profiler [3]: The technique is based on cross correlations among the different WFS slopes. The profile is obtained by getting the energy along the baseline between two WFS positions. The method also provides altitude, speed and direction of layers. The figure shows the profile between a WFS at the centre with another at the corner

Figure 3 shows some results from GeMS profiler. On the top, the profiles for the night of April 16th 2013 are presented. The central bar plots show histograms for r_0 and θ_0 for different campaigns during 2012, 2013 and 2014. The bottom panels show a bar plot (left) quantifying the turbulence energy of the remaining residuals (performance of the AO system) and on the right, a polar plot with high altitude wind direction and magnitude along these three years is presented.

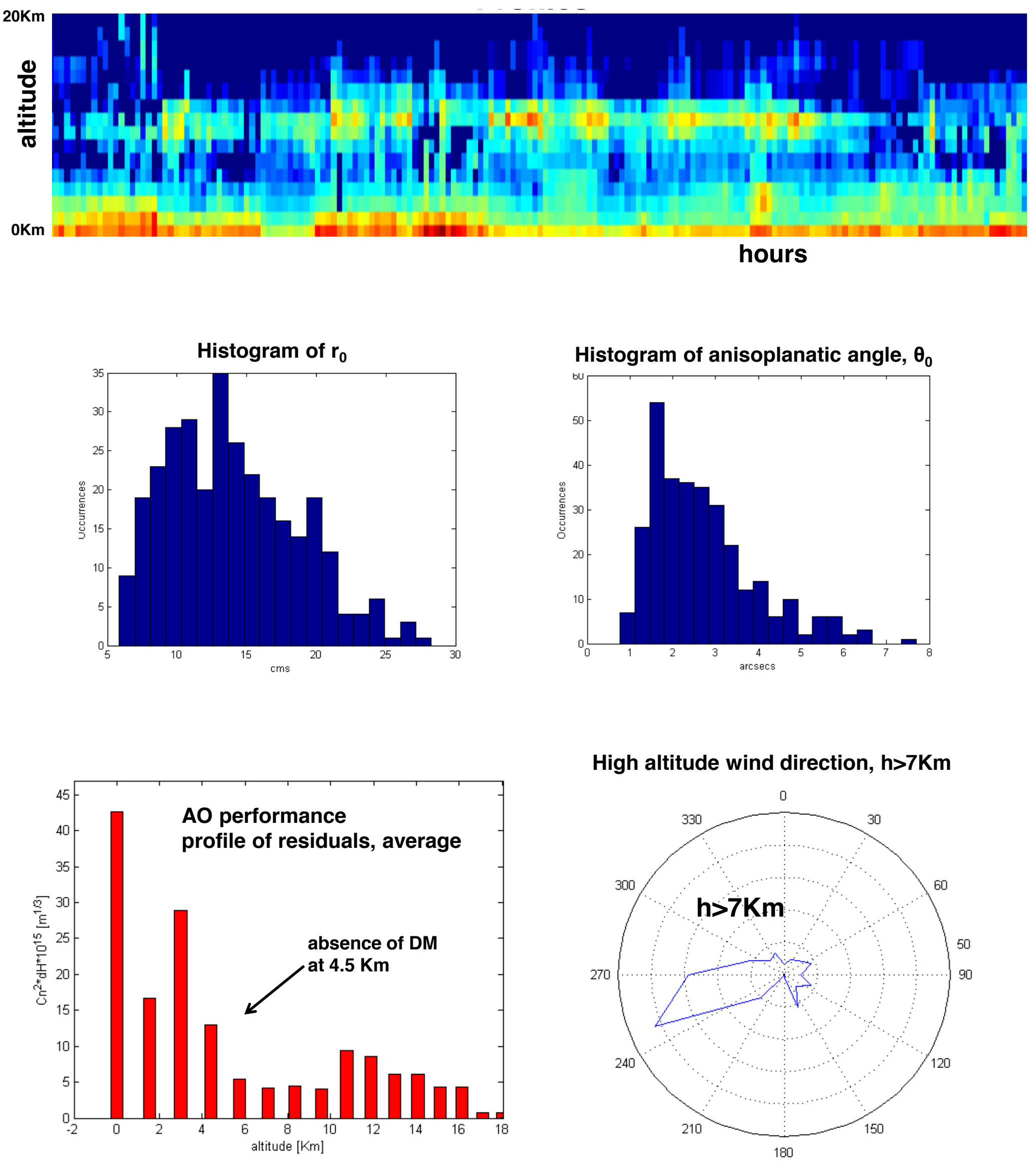

Figure 3. Some statistics from GeMS profiler. Top:Cn^2 profile for a complete night; Center: histograms for r_0 and θ_0 ; Bottom left: loop residual profile (useful to evaluate AO performance); Bottom right: polar plot for wind magnitude and direction

Another interesting study carried out with GeMS profiler was to estimate the decay in the decorrelation of the turbulence layers in time, i.e. how frozen the layers are. Figure 4 shows the main result. Here, it was found that a nearly linear dependence exists in the temporal correlation of the layers as a function of the travelled distance. This behavior showed that the decorrelation does not depend in altitude nor wind speed.

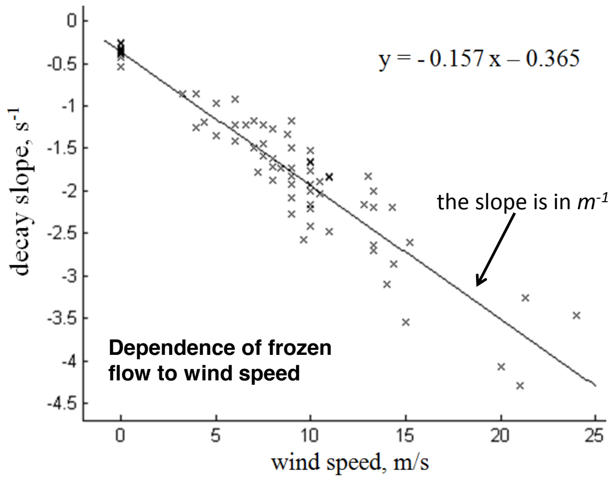

Figure 4. Plot with decay ratios of turbulence layer decorrelation (frozen flow assumption) [4]

Nevertheless, an important parameter of turbulence that was still not estimated with the method, was the global outer scale L_0 and its altitude profile $L_0(h)$. The next sections briefly describe the first approach to solve this estimation problem on-line. Results obtained from the telemetry data collected from GeMS along 3 years of campaigns are also presented.

3. ESTIMATING THE GLOBAL L_0

We started by developing a method for estimating the global outer-scale based on fitting the autocorrelation function obtained from the telemetric pseudo-open-loop slopes, to a combination of simulated functions using Von Karman turbulence models.

Figure 5 (top) shows two autocorrelation functions obtained from simulated slopes for turbulence cases with outer scales of 1m and 50m. The shape in each case are very distinctive, especially in terms of their width. A negative sidelobe is also very clear for the shorter L_0. At the bottom of the figure, several slice cuts of this function for different values of L_0 are plotted.

Notice that as the L_0 value grows above 30 m, the functions tend to be very similar, making the problem ill-conditioned. This restriction, caused by the diameter of the telescope, restricts the range of estimation to values of L_0 up to 50 m. Simulations have shown that values larger than 4 or 5 times the telescope diameter are highly unreliable.

Our first attempt to solve the estimation problem was to fit theoretical autocorrelation functions to the one obtained from onsky data. Unfortunately, there were two reasons that made this approach unsuccessful. Firstly, a good estimation of noise is required in order to extract its contribution from the measured autocorrelation function. Several methods were tried to estimate the noise, such as 1-frame delayed correlations, polynomial fitting around the central peak and estimation of the noise from the higher end of the rejection function power spectral density of the AO loop. None of them proved to be robust enough in all cases.

The other reason that prevented a good estimation of the response function, was the fact that very often, the autocorrelation is formed by the combination of responses coming from layers at different altitudes and with different outer scales. This is clearly exemplified in figure 6, where an autocorrelation obtained from real onsky data shows that more complex functions may appear when two or more different outer scales exist along the line of sight.

From the latter results, we soon realized that estimating a global L_0 has no significance due to this multimodal effect, so a more drastic approach was undertaken.

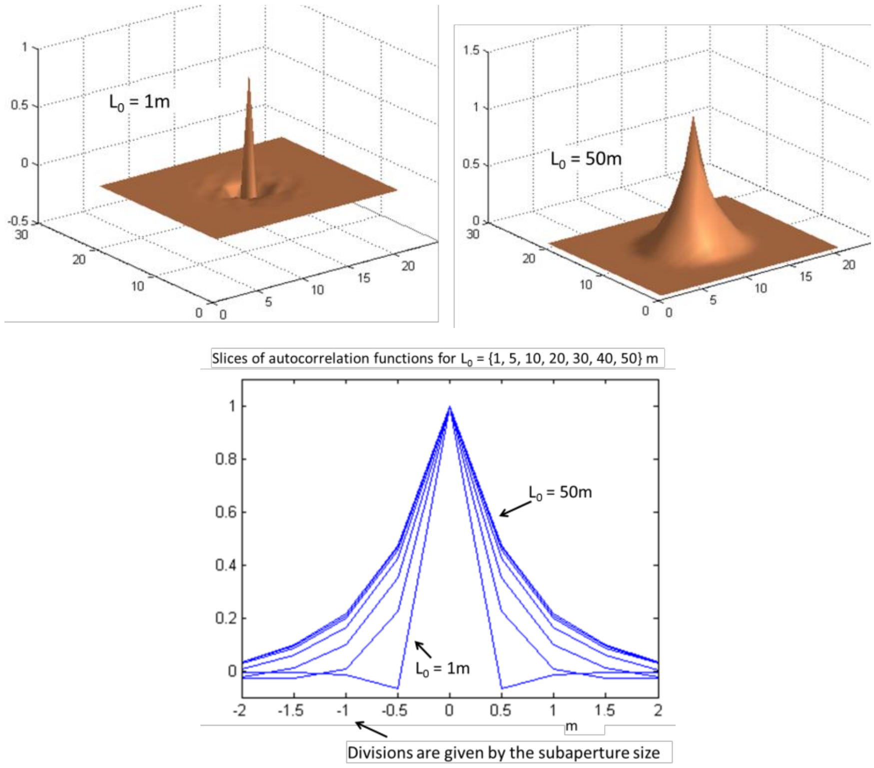

Figure 5. Simulated response functions (autocorrelations of slopes) for GeMS

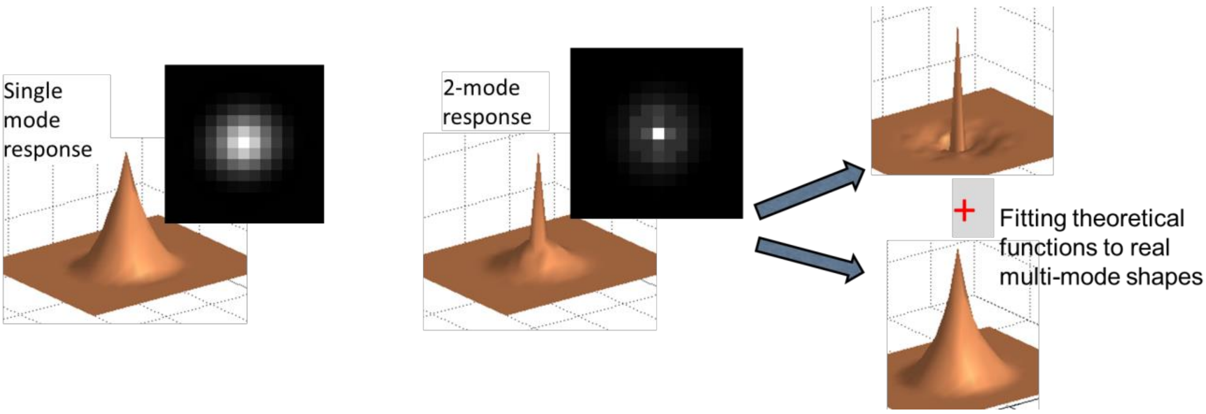

Figure 6. Onsky response functions (autocorrelations of slopes) from GeMS telemetry data. Left: response from a single L_0; Center: two mode response with small and large values of L_0; Right: decomposition of the two-mode response in two response using theoretical response functions

4. ESTIMATION OF THE OUTER SCALE PROFILE, $L_0(h)$

The poor results using autocorrelation functions lead us to base the estimation of L_0 solely on cross-correlations from the five wavefront sensors available in GeMS. This method eliminates the two causes of failures mentioned above: the estimation of detector noise and the presence of multiple values of L_0 in altitude.

Next, this cross-correlation approach is described using onsky data. The technique starts by deconvolving the raw cross-correlation maps with a response function corresponding to a large L_0 (wide function), defined arbitrarily. This generates negative values around those correlation peaks where small L_0 exist (e.g. at the ground). By forcing symmetry in these bins, its response function can be separated from the rest and convolved back in order to find its L_0 value(s) by fitting theoretical functions with different L_0.

The response function at the ground is subtracted from the rest of the cross-correlation map, and by iteratively applying a this approach to the remaining map, the outer scale of the higher bins can also be estimated. This is illustrated in figures 7 and 8.

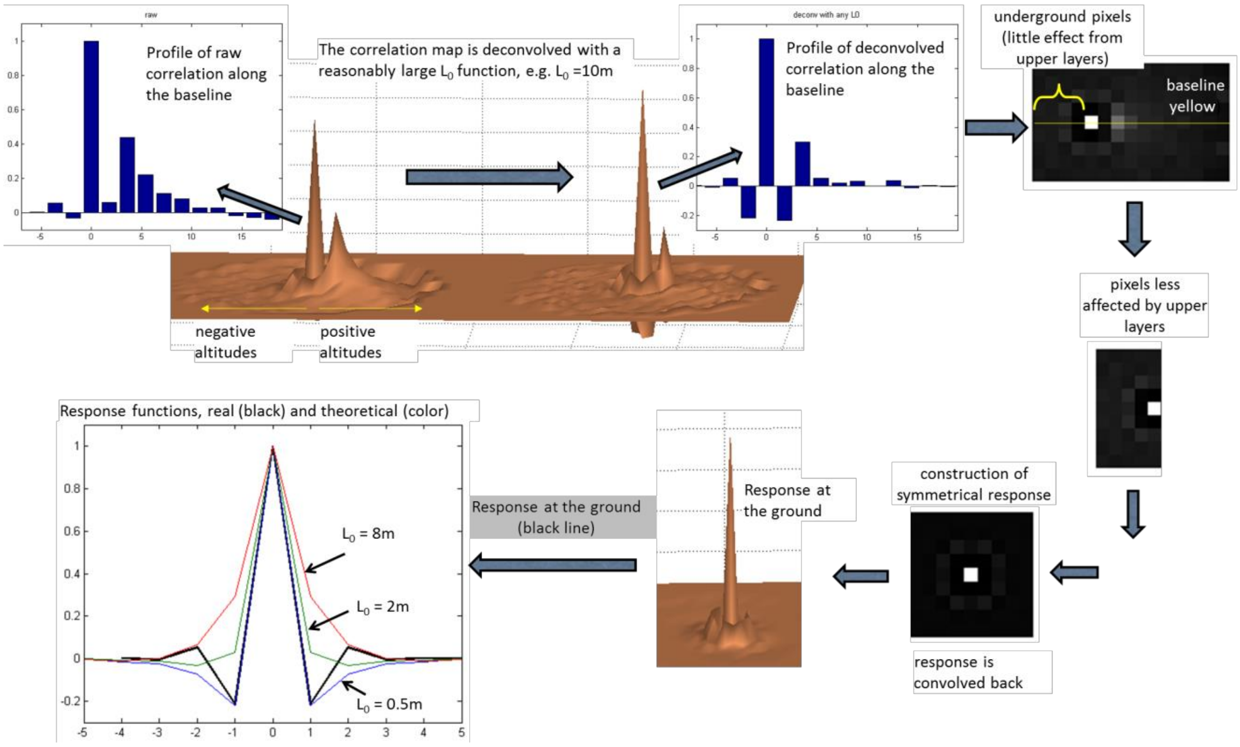

Figure 7. The method to estimate the outer scale profile. The convolved response functions are progressively separated in their constituents, by individually deconvolving and subtracting each layer

Notice that the resulting function at the ground departs from the theoretical ones (Fig. 7, bottom left). Two possible causes for this difference are that the turbulence probed does not follow Kolmogorov statistics and another could be explained by the presence of a second layer in the first bin.

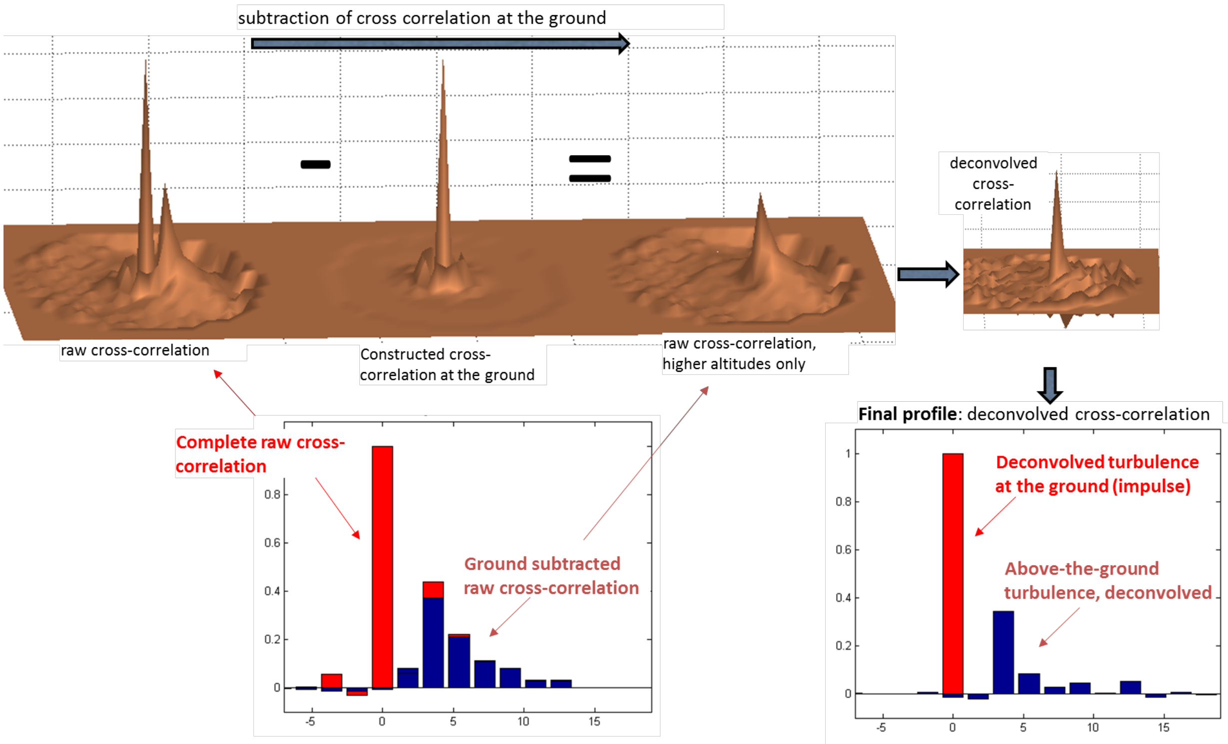

Figure 8. Resulting profile after deconvolving the response at the ground and then the remaining higher layers

5. RESULTS

In order to overcome the problem pointed out in the previous section, a method (not presented here) based on fitting theoretical functions to the cross-correlation from the telemetry data has been developed. The next figure, shows the profile for the outer scale - $L_0(h)$ – for 1195 samples. The profile has been divided in slabs of 2Km, except for the two divisions closer to the ground. The abundant data available in the first 2 Km allowed us to further divide it into two slabs 1Km each.

An average of 22.8 m and a median of 16.4 m were estimated for the complete set of samples. However, we think that these values are misleading and cannot be used, for two reasons: i) the estimation range has been limited at 50 m due to the telescope blindness for larger values L_0; ii) in many altitude segments, multimode histograms are found which make a single scalar meaningless. For instance, the bar plot on the right (histogram of the first 1 Km slab), clearly detects at least two modes at both extremes (1m and 50m).

An arbitrary exercise of further dividing the first bin is carried out, assuming that the shorter values of L_0 will tend to populate the boundary layer (a strong assumption indeed). In this case the original profile values marked with diamonds (bottom of left panel) are replaced by asterisms in the lower part of the profile.

In any case, however, the profile has many characteristics common to other previously reported profiles obtained in independent campaigns (e.g. [1] and [2]), where the maximum values for L_0 are obtained for altitudes between 1 and 2 Km and the smaller are located around 4 Km.

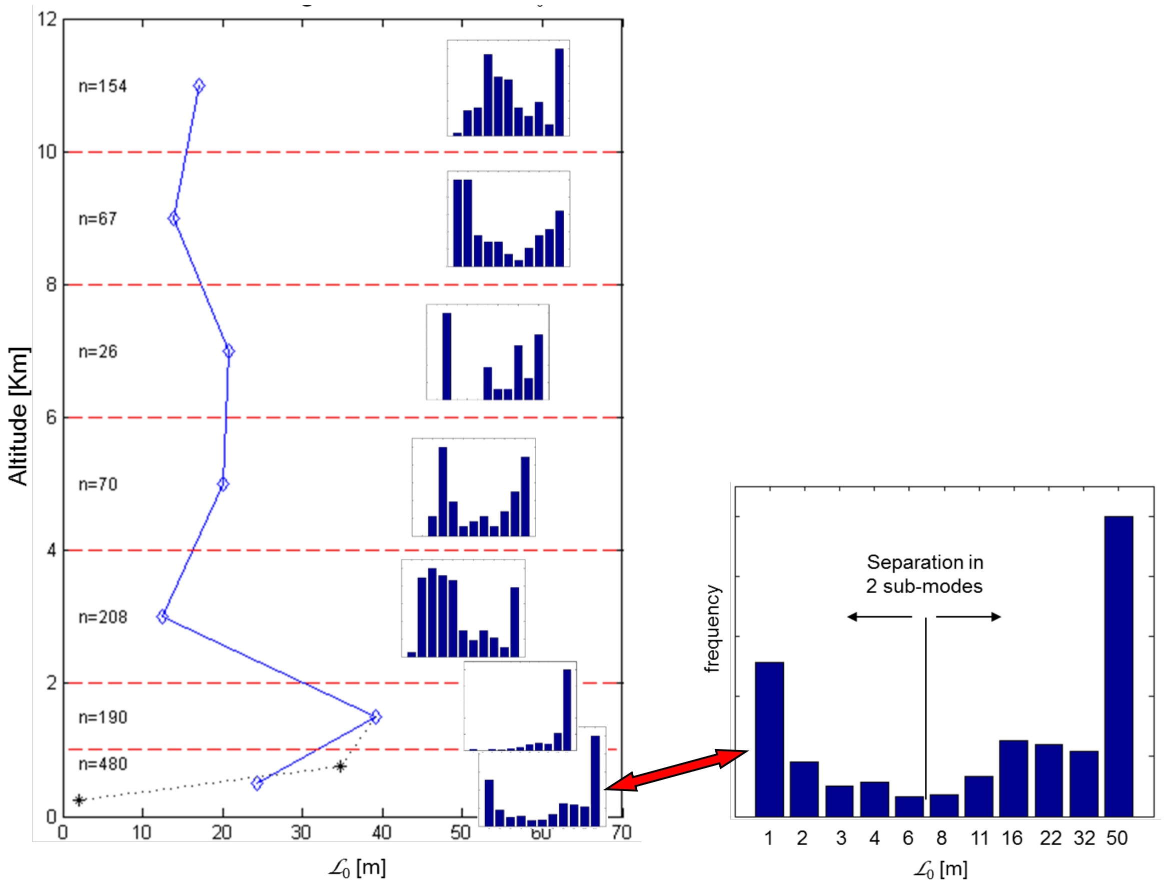

Figure 9. Profile of outer scale for the three year data. The profile has been divided in slabs of 2Km, except for the first one, which thanks to the abundant data available it is further divided in two slabs 1Km each. In many altitude segments, multimode histograms are detected. The bar plot on the right shows two modes at the extremes of the range for the lowest segment. Asterisms correspond to an additional division of the bottom part of the profile according to the size of the estimated values of the outer scale.

6. CONCLUSIONS

We have shown, using data from GeMS, that all turbulence parameters can be estimated by means of processing pseudo-open loop slopes from telemetry data and actuator voltages. We have also presented results obtained from a new method to determine the atmospheric outer scale profile - $L_0(h)$ – based on fitting simulated cross-correlation functions to the cross-correlation maps computed from the measured slopes. Significant similarities exist between our results and other previously reported campaigns.

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